Parametric studies and the operating latitude of a spectrally narrowed KrF excimer laser for the deep UV stepper

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ABSTRACT

With the near certainty that the excimer stepper will become one of the lithography tools for printing sub -0.4 μm design rule features, it has now become imperative to better understand the performance characteristics of the excimer laser in the context of the total lithography process. It is no longer possible to treat the laser in isolation from the stepper or the resist. The cost of operation for the laser is integrally tied with the stepper specifications, design rule requirements and resist characteristics.

This paper discusses the dependence of laser parameters on stepper performance, and the relationship between various laser operating parameters and specification. In addition, it analyzes the combination of the laser to the lithography process cost per wafer level in terms of design rule requirements and resist characteristics.

1. INTRODUCTION

The excimer laser based stepper is now expected to become one of the primary lithography tools for printing sub -0.4 micron design rule features for the next generation of I.C. devices (Ref. 1). With the recent introduction of production worthy excimer steppers with high NA and wide field lenses, the overall performance requirements for the laser have become more stringent in terms of specifications, component reliability and operating costs. Table I presents both the stepper performance and the corresponding laser specifications over three generations of excimer steppers models.

Table I - Stepper Performance & Required Laser Specification

STEPPER	**1st (1988/89)**	**2nd (1990/92)**	**3rd (1993/94)**
NA	0.35	0.4 - 0.45	0.35 - 0.53 (variable)
Field Size (mm)	21 Ø	21 Ø , 25 Ø	> 30 Ø
Optical throughput Efficiency	5 - 8%	≥ 10%	≥ 15%
LASER			
Spectral bandwidth:			
FWHM (pm)	≤ 3	≤ 2.2	≤ 1.3
95% Energy Band (pm)	- - -	< 7	< 4
Center Wavelength Stability (pm)	≤ ± 1	≤ ± 0.5	≤ 0.25
Pulse Energy Variation (σ)	≤ 3.5%	≤ 3 %	≤ 2.5 %
Power	2-3W	4W	6W
Repetition Rate (Hz)	200	400	500

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To better understand the excimer stepper and the lithography process, it is helpful to establish a relationship between laser parameters and corresponding stepper performance. This is presented in Table II.

Table II - Laser Parameters vs Stepper Performance

Spectral Bandwidth and Spectral Energy Distribution	⇨	Resolution, Depth of Focus
Relative Wavelength Stability	⇨	Focal Plane Stability (long term) Resolution, D.O.F., (Short Term)
Absolute Wavelength Stability	⇨	Magnification, Distortion
Output Power	⇨	Throughput
Repetition Rate	⇨	Energy Dose Accuracy, Speckle Reduction,
Pulse-to-Pulse Energy Stability	⇨	Energy Dose Accuracy,
Beam Profile, Beam Pointing & Beam Divergence Stability	⇨	Exposure Uniformity, Illuminator Efficiency
Polarization Stability	⇨	Illuminator Efficiency
Spatial Coherence	⇨	Speckle, Exposure Uniformity

⇨ implies affects

From Table II we can conclude that in order to achieve high productivity and a cost effective process the laser has to meet all specifications simultaneously. In addition, the overall operating cost of the laser has to be low.

Of all the performance parameters discussed in Table I and II, the two most challenging are the spectral bandwidth and the pulse-to-pulse energy stability. In this paper, we will analyze the behavior of these two specifications under various operating conditions and their relationship to resolution and DOF, stepper NA, energy dose accuracy and resist characteristics. Such an analysis will allow the IC device maker to select a suitable resist process and set up the most cost effective laser maintenance schedule to achieve the desired resolution with the maximum DOF.

2. BASIC PRINCIPLES OF EXCIMER LASER OPERATION

All excimer lasers developed for lithography applications use an electric discharge to excite and ionize the gas to produce the laser upper state KrF* molecule (Ref. 2). When this excited KrF* molecule decays to the ground level, through disassociation into Kr and F, it liberates a photon at 248 nm. The number density of KrF* exponentially increases as the discharge grows, and so does the gain. Once the gain exceeds a threshold value, lasing starts. Spectral narrowing is achieved by feeding only a particular frequency component of the light back to the active gain region. The frequency selection process takes place in the line-narrowing module using dispersive optical elements. The feedback signal is amplified as the light propagates through the laser plasma by the stimulated emission process, and the spectrally purified

high intensity radiation emerges from the output coupler. A part of the light is reflected by the partially reflective output coupler and fed back to the gain region.

The gain depends on the ratio of three gas constituents; F_2, Kr, and Ne, and the total gas pressure. The gain and the optical cavity configuration determine the laser output power. Dispersion characteristics of the line-narrowing module and the discharge characteristics define the spectral quality of the output. In addition, discharge uniformity and the gas flow consistency influences the pulse-to-pulse stability. There is a strong interdependence between laser efficiency, gas pressure and composition, pulse energy stability, bandwidth, laser beam profile stability and discharge electrode life.

The electrical discharge circuit that ionizes the gas to create the gain medium is based on transferring electrical energy (2.5 J) from a main capacitor C_1 charged to high voltage (12-14 kV) into the laser gas using a pair of electrodes in approximately 30 ns. The gain medium thus set up has typical dimensions of 50 cm x 1.6 cm x 0.5 cm. The two electrodes are approximately 50 cm long and are separated from each other by 1.6 cm. See Figure 1.

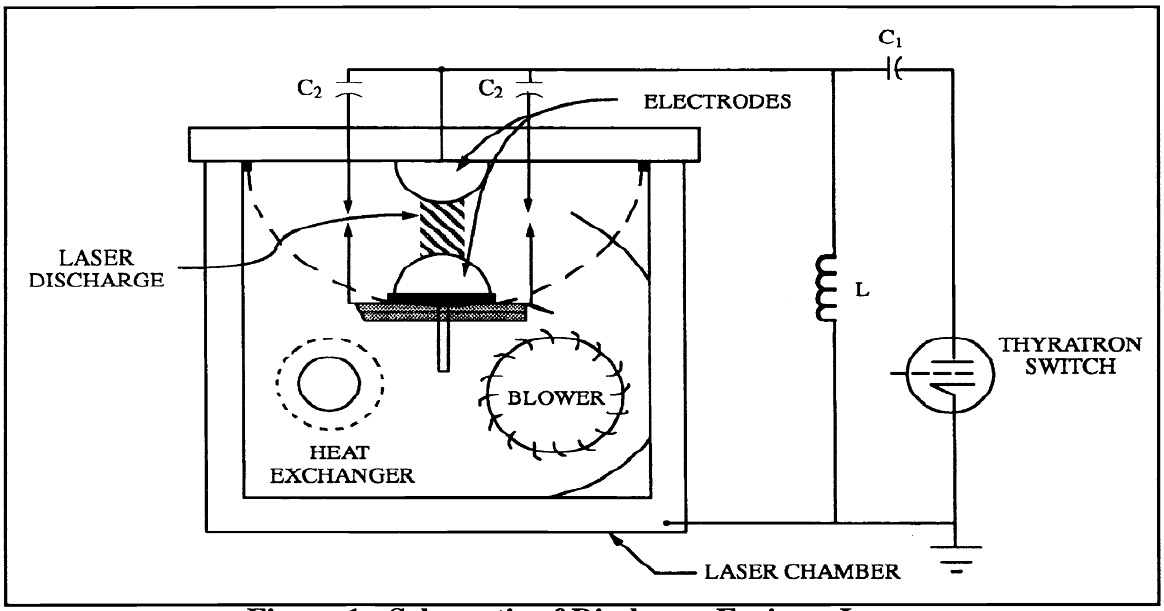

Figure 1 - Schematic of Discharge Excimer Laser

However, not all the energy stored in the main capacitor is transferred to create the gain medium. Some of it is lost due to impedance mismatch and non-optimum operating conditions. The lost energy is the major cause for electrode erosion. Laser efficiency is defined as the ratio of output pulse energy to the initial stored energy in the main capacitor. In an efficient laser, electrode erosion rate is less. The discharge takes place repeatedly at 400-500 Hz and after each discharge a certain amount of electrode material is lost due to electron and ion bombardment followed by passivation by the fluorine gas. Before each pulse fresh gas has to be introduced between the electrodes to assure good energy transfer and discharge stability. Inadequate gas exchange between pulses leads to poor pulse energy stability.

The erosion of electrodes has three direct consequences; First, loss of fluorine due to electrode passivation after each pulse; Second, increase in discharge cross section; Third, creation of metal fluoride dust.

The first effect can be compensated for by injecting small amounts of fluorine periodically to make up for the loss. The next two affects have longer term consequences. An increase in discharge cross section leads to increases in beam size, beam divergence and spectral bandwidth. Increases in beam size and beam divergence may result in exposure non-uniformity at the wafer and some loss in optical throughput efficiency. However, this problem can be solved by minor adjustments in the beam transport optics during routine maintenance. An increase in spectral bandwidth, on the other hand, is more serious since it leads to loss of resolution and DOF. It is the primary cause for replacing the discharge chamber.

Finally, the metal fluoride dust which is created in the chamber tends to settle on the optical windows leading to loss of efficiency and higher operating voltages. Furthermore, scattering from dust on the windows leads to increase in spectral bandwidth. Both these effects are minimal in a properly designed chamber with an effective window protection system (dust filter). However, the windows can be cleaned periodically when the performance deteriorates beyond a certain level.

The rate of electrode erosion is affected by laser efficiency, level of contamination in the chamber and fluorine concentration. All these parameters can be optimized to reduce electrode erosion to a minimum. For example, the use of only ceramics and metals inside the chamber reduces the levels of gaseous contaminants, such as CF_4, SiF_4, HF and COF_2, to negligible levels. Such a chamber has low electrode erosion, low fluorine consumption, long gas life, and a low level of metal fluoride dust creation.

In the next section, we will discuss the relationship between pulse-to-pulse energy stability and laser efficiency.

3. PARAMETRIC STUDIES

This section discusses the dependence of pulse energy stability and the spectral bandwidth on fluorine concentration, operating pressure, and the operating voltage (Ref. 3). The nominal gas composition was 0.1% F_2, 1.2% Kr, balance Ne at a pressure of 315 kPa. The laser used for the studies in this paper is equipped with a second generation line narrowing module (bandwidth $\leq$ 2.2 pm, FWHM) but is being operated at 500 Hz, 6W.

Figure 2 illustrates the relationship between pulse energy stability and fluorine concentration. The data was taken with the laser operating in a burst mode (0.33 sec on, 0.30 sec off), at a pulse energy of 12 mJ at 500 Hz. A voltage tailoring algorithm was used to minimize pulse energy spiking during the initial part of the burst. As is evident, pulse energy fluctuations increases with increasing fluorine concentration; almost 25% increase in σ for 20% increase in F_2 concentration. This figure also gives the rate of fluorine consumption as a function of the number of pulses; 0.017 kPa per 10^6 pulses.

The corresponding operating voltage behavior is shown in Figure 3. Note the decrease in operating voltage, thus increased efficiency, after a fluorine injection.

Similarly, we have plotted the HV required along with the corresponding pulse energy stability for operating the laser at 12 mJ/500 Hz as a function of the total gas pressure, Fig. 4. The laser was operated in burst mode as described earlier. Fluorine concentration was set at 0.35 kPa. Note that at low pressures the efficiency is low, while at high pressure pulse energy stability deteriorates. These two figures have

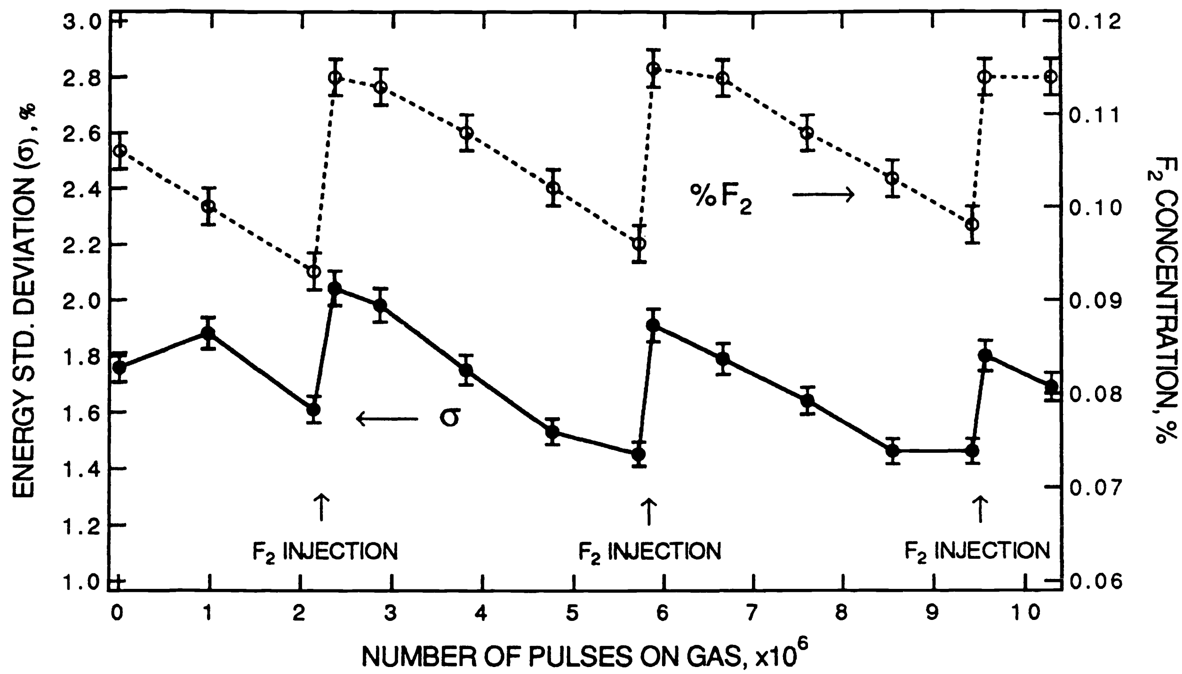

Figure 2 - Dependence of Pulse Energy Stability on F_2 Concentration. Note the 25% increase in pulse energy variation (σ) for 20% increase in F_2 concentration. Laser was operated at 12 mJ/ 500 Hz in a burst mode sequence of 0.33 sec on / 0.3 sec off.

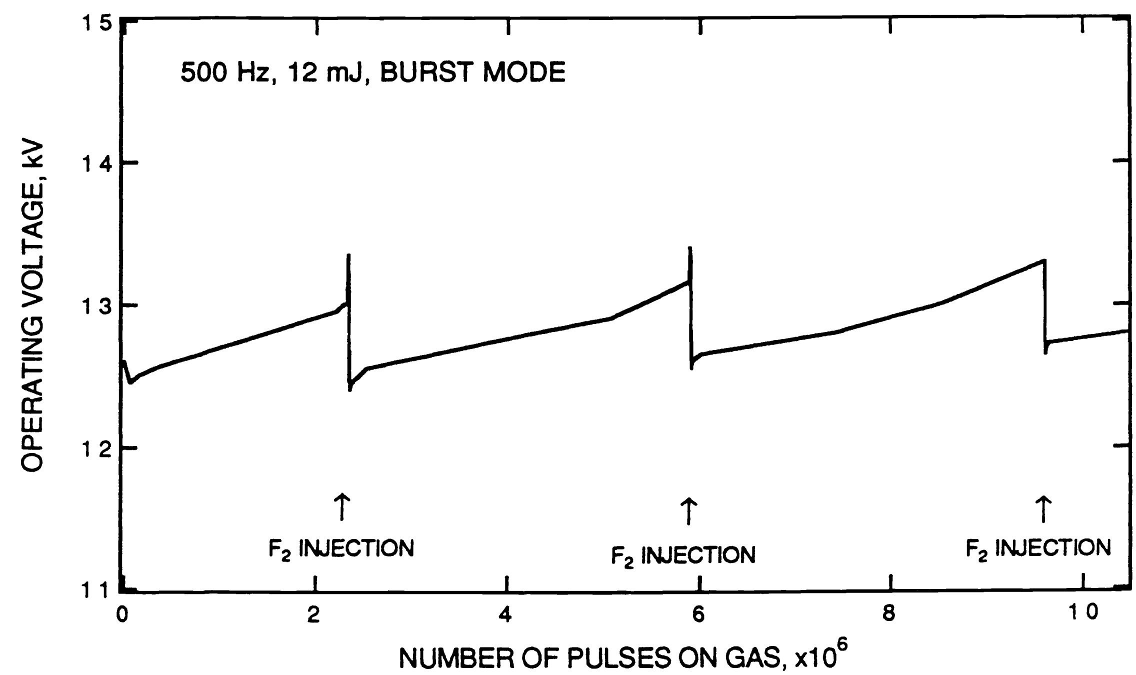

Figure 3 - Laser operating voltage during 10^7 pulse run. Laser operating in burst mode, at 12 mJ/500 Hz. Note the decrease in operating voltage after an F_2 injection.

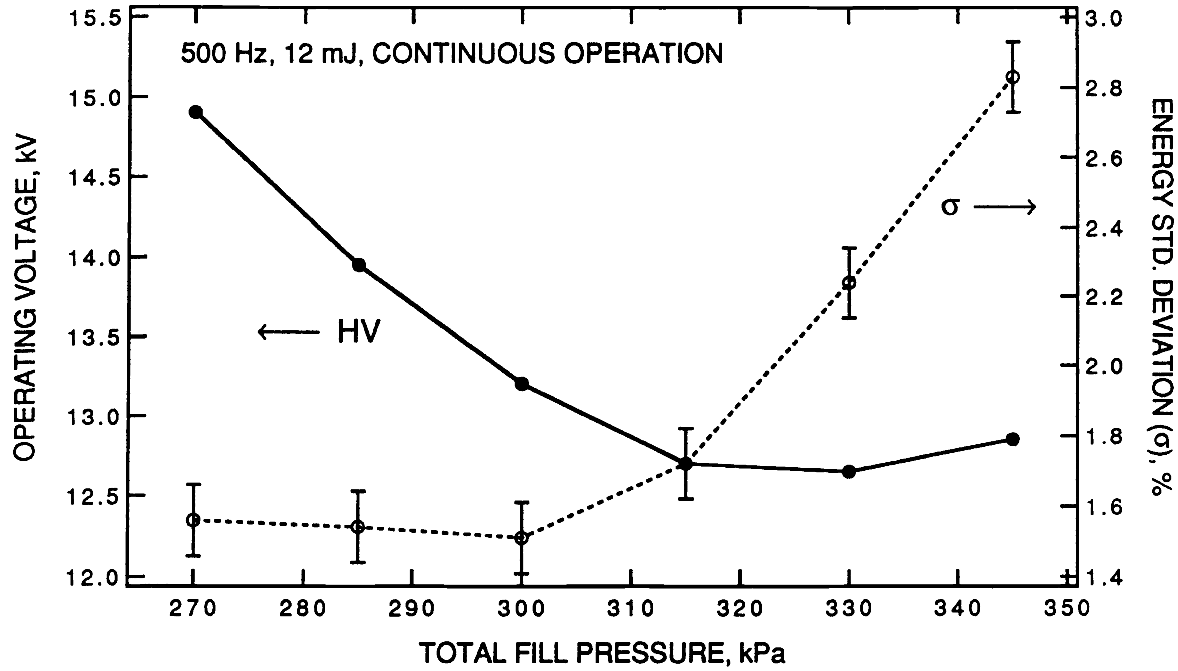

Figure 4 - Dependence of charging voltage and pulse energy stability on the gas pressure. The laser was operated to achieve 12 mJ at 500 Hz in a continuous mode. F_2 partial pressure = 0.35 kPa.

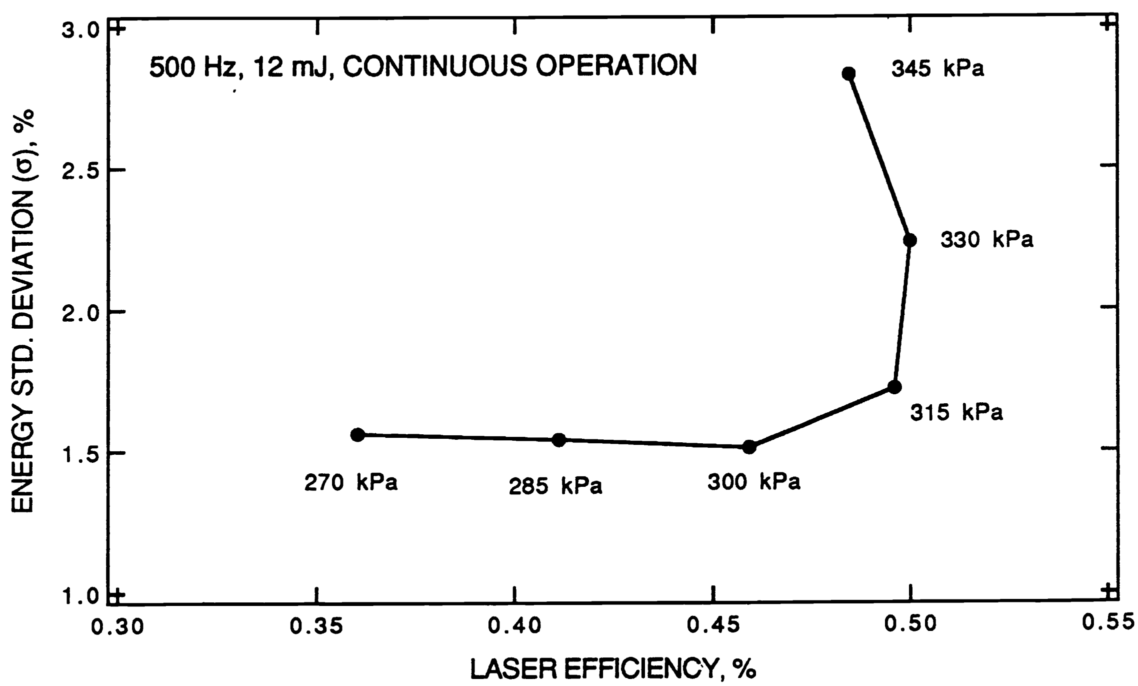

Figure 5 - Pulse Energy stability versus laser efficiency over a range of operating pressures. F_2 partial pressure = 0.35 kPa. A reasonable compromise between minimum σ and maximum efficiency occurs at 315 kPa fill pressure.

been combined in Figure 5. Optimum performance (lower right corner) is achieved when the laser is operated at a pressure of 315 kPa.

Figure 6 illustrates the relationship between pulse energy stability, laser efficiency and a normalized operating voltage. The data was taken with the laser operating continuously at 500 Hz with the operating voltage being increased from 12 kV to 17 kV in steps of 0.5 kV. Voltage V_b is the minimum voltage at which the discharge occurs - (breakdown voltage). It is a function of the gas pressure, electrode separation and gas composition. For the laser under test $V_b = 10.6$ kV. Figure 6 shows that for $V/V_b \approx 1.35$ the laser efficiency achieves a maximum but the pulse energy stability does not reach a minimum. This was also confirmed from Figures 2, 3 and 5, that the highest efficiency and the best pulse energy stability can not be achieved simultaneously. Therefore, if a stringent pulse energy stability is specified, then the laser efficiency is not optimum. As a consequence, electrode wear rate and fluorine consumption rate will be higher resulting in higher operating costs.

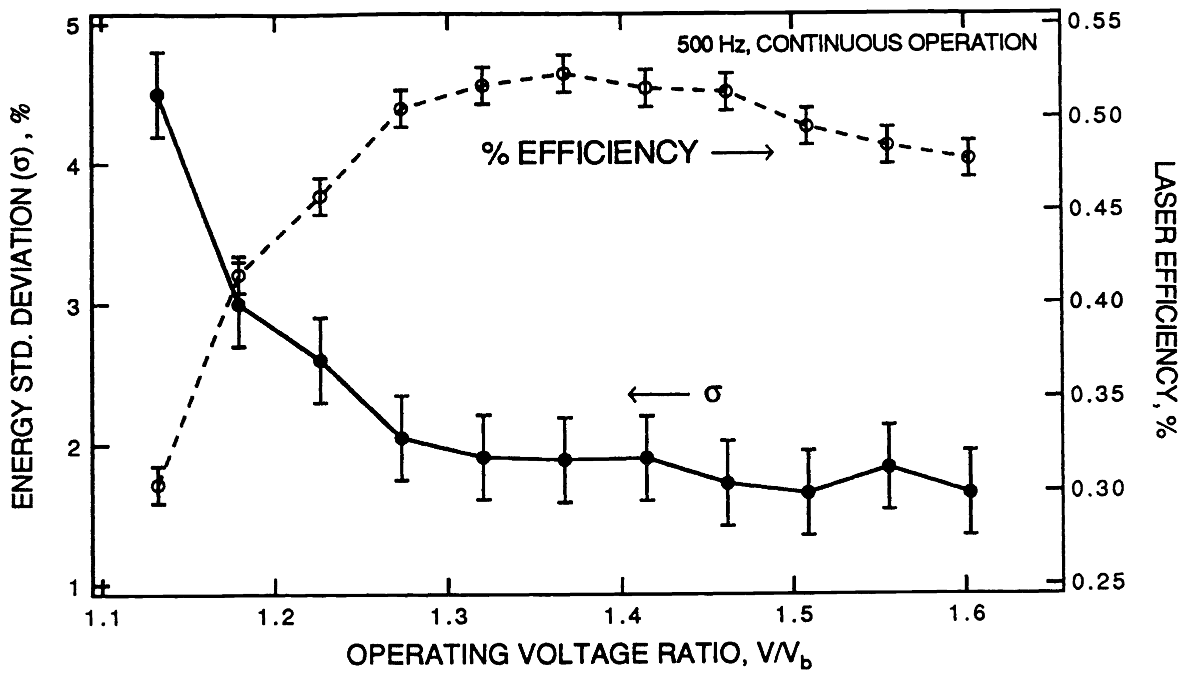

Figure 6 - Pulse energy stability and laser efficiency as a function of normalized operating voltage. Vb ≈ 10.6 kV. The laser was operated in continuous mode 12 mJ/ 500 Hz.

However, with the incorporation of more inert chamber materials and an improved fluorine injection scheme, it will be possible to select a suitable operating condition that will result in long electrode life along with good pulse energy stability. Fluctuations in fluorine concentration, especially during injections, have to be minimized in the future.

The change in the laser output spectral bandwidth as a function of fluorine concentration is shown in figure 7. Note the small increase in bandwidth, especially the 95% energy band, after a fluorine injection. Once again it illustrates the need to control the fluorine concentration precisely and accurately. The spectral

bandwidth was measured on a grating spectrometer with a resolution of 0.25 pm. Note that the laser has a second generation line narrowing module (bandwidth ≤ 2.2 pm FWHM).

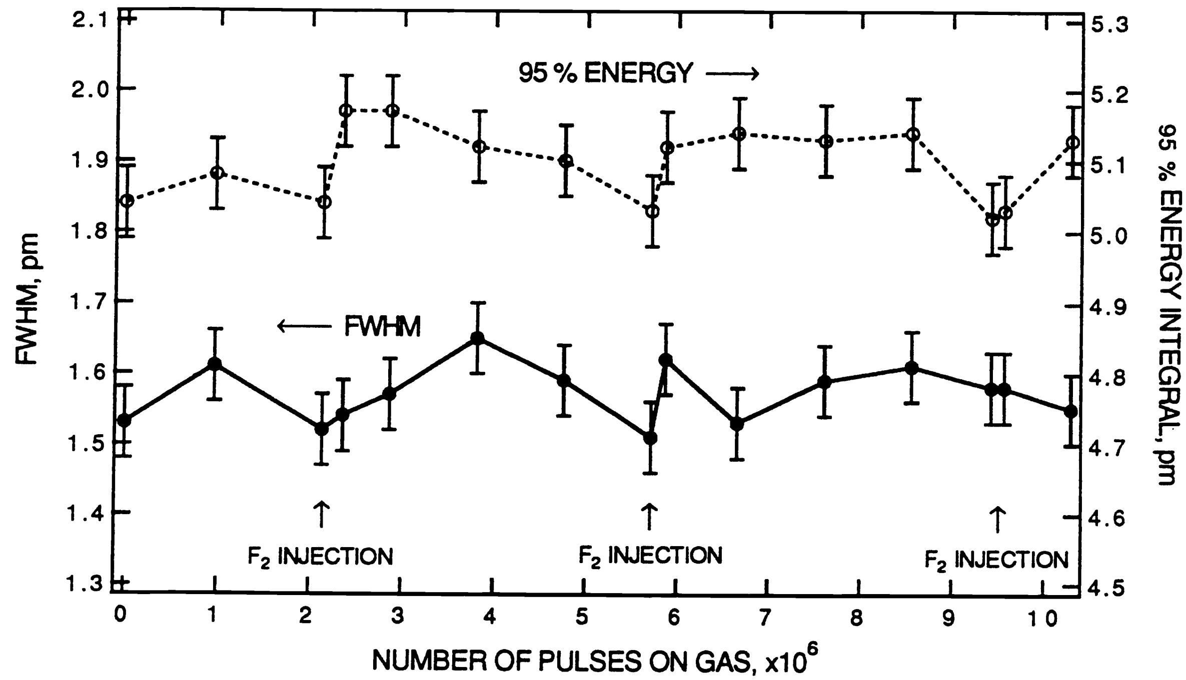

Figure 7 - Spectral bandwidth versus number of pulses and F_2 concentration. Note the increase in bandwidth after an F_2 injection.

4. DISCUSSION AND SUMMARY

This section summarizes the observations of previous sections and presents a process for lowering the laser operating cost.

Section 1 presented the relationship between stepper performance and laser parameters. Section 2 discussed the basic principles of excimer laser operation and the effect of electrode erosion on laser performance; in particular, the increase in spectral bandwidth. We noted that electrode erosion is directly affected by laser efficiency: the lower the efficiency, the greater the electrode erosion rate. The relationship between pulse energy stability and laser efficiency was discussed in Section 3. It was shown that a stringent pulse energy stability requirement leads to less than optimum laser efficiency. Therefore, if an optimal resist sensitivity is chosen, which will allow for more laser pulses but with a relaxed energy stability specification for exposure, then one can operate the laser more efficiently thus resulting in a lower electrode erosion rate and a lower operating cost. However, too low a resist sensitivity will require many more pulses, thus resulting in a higher operating cost.

The cost of operating a laser is driven by:

1. Level 1 consumables, such as laser gas, fluorine trap, windows, and facility requirements.

2. Level 2 consumables, such as electrode replacement in chamber, pulse power module and line narrowing optics.

The major contributor to the laser operating cost are the level II consumables, specially the cost of replacing the electrodes in the discharge chamber. Other contributors to the cost are presently not significant. The laser discharge chamber is replaced primarily because of electrode erosion and increase in spectral bandwidth. However, what is an acceptable spectral bandwidth? If the bandwidth specification is 1.3 pm (FWHM), does the chamber become unusable if the bandwidth increases to 1.4 pm or 2.0 pm?

It is well known that depending on the resist process there is an optimum NA which yields the maximum DOF for a certain resolution (Ref. 4). As an example, for a resolution of 0.35 μm, an NA of 0.45 will yield a DOF of 1.2 μm when used with a high contrast deep UV resist. An NA of 0.45 μm requires a laser with a spectral bandwidth of 2.2 pm (Fig. 8). Consequently, a laser beginning with a bandwidth of 1.3 pm will have an operating latitude of approximately 0.9 pm before it becomes unusable. However, for a resolution of 0.3 μm the optimum lens NA may be 0.5 which requires a spectral bandwidth of 1.7 pm. In this case the operating latitude for the same laser will be 0.4 pm. The operating cost in the second case will therefore be higher.

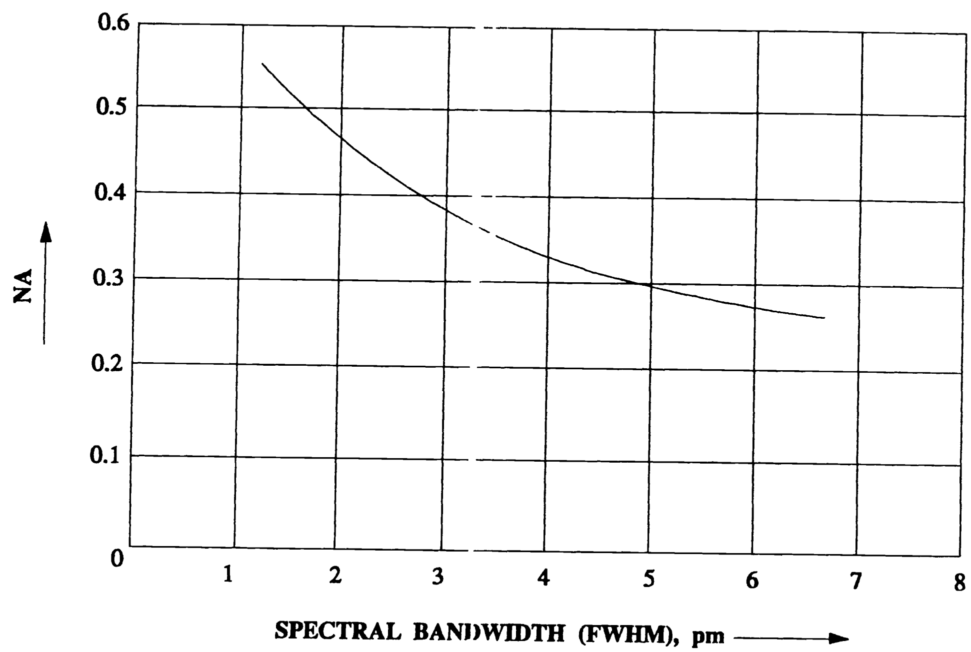

Figure 8 - Stepper Lens NA Versus Spectral Bandwidth of KrF Lasers (248 nm)

Furthermore, it should be noted that the spectral bandwidth specification that truly affects the lens performance is the 95% energy band and not the FWHM (Ref. 5). In lifetime tests conducted at Cymer, we have observed that when the electrodes wear out the 95% energy band is less affected compared to the FWHM. It is therefore important not to rely just on the FWHM measurement to establish chamber lifetime.

Laser operating cost per wafer level is therefore a function of a.) resist characteristics (sensitivity and contrast), b.) resolution and DOF requirement (NA of lens), c.) Optical throughput efficiency, and d.) energy dosage control scheme. Therefore, in order to determine the true cost of operation one has to take into account the total process and its requirements.

One of the simplest approach to reduce cost of operation is to improve the chamber materials and increase the efficiency to reduce electrode erosion. However, an additional avenue is to begin with a spectrally narrower system than required to increase the operating latitude. This is achieved by using a more highly dispersive line narrowing module.

With this in mind we are introducing the ELS-4000D laser, suitable for cost effective 0.3 to 0.4 μm design rule lithography. Its specifications are 12 mJ at 500 Hz, with a bandwidth of ≤ 1.3 pm (FWHM) and 95% energy in < 4 pm. See Table I, Column 3. The maintenance schedule for this laser is given in Table III.

Note, that except for gas exchange and fluorine trap replacement, other action items call for checking performance before proceeding to replace the part or the module. The intervals shown here are minimum values and are for reference. To improve stepper uptime and availability, it is preferable to synchronize the laser maintenance schedule with the stepper maintenance schedule. Under these conditions the total cost of operating the laser in 1993 for printing 0.35 - 0.4 μm features for 1000 million pulses will be less than $25,000. In the future this cost is expected to decrease by an additional 20-30%. It will then compare favorably with using an i-line mercury lamp for a year.

Table III - Maintenance Schedule

Gas Exchange	25 M or 3 days
Fluorine Trap	100 Refills
Window Inspection / Clean [1]	>500 M
Optics Inspection / Exchange[1]	> 1000 M
Inspect, Recalibrate & Qualify Laser [1]	> 1000 M
Laser Chamber (min.)[2]	> 2000 M
Line Narrowing Module (min.)[2]	> 3000 M

[1] Check base line performance: voltage vs. energy, bandwidth. Recalibrate if necessary.

[2] a. Check base line performance: voltage vs energy, bandwidth, pulse energy stability.

b. Phototest - resolution vs DOF

5. CONCLUSION

This paper concludes that in order to reduce the contribution of the laser to the lithography operating cost per wafer level, it is important to look at the total lithography process. This includes stepper requirements and its design features, resolution and DOF requirement, an optimum value of lens NA, and the resist characteristics. Unlike a lamp, it is no longer possible to treat the laser in isolation from the stepper or the process.

6. REFERENCES

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